Chapter 30

Thermal Simulation of 10 MeV Linac Cavity

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The 10 MeV RF Linear accelerator (linac) based electron accelerator is operational at Electron Beam Centre, Kharghar at 3 kW average beam power. The linac cavity which accelerates the electron particles up to energy of 10 MeV has 33 cells cavity structure fabricated in three parts. Of these, the top and bottom parts consist of 14 cells each while the middle part has 5 cells, including the power feed cavity (middle portion). The thermal analysis of the structure is presented here.

30.1 Analysis Methodology

The material of construction for the cavity is OFE Copper with SS flange brazed at its end for mounting. The cavity is subjected to symmetric heat load during its operation. Water cooling is provided to maintain its temperature within the permissible limit and therefore reduce the detuning effect of cavity due to frequency change by thermal deformation. Water cooling Cu tubes are brazed to the cavity spirally over the cavity surface. The thermal-structural analysis of the cavity is carried out in ANSYS mechanical APDL to determine the temperate distribution and deformation in the cavity due to its heat load and water cooling provided. Though analysis reveals the shortfalls in the cooling design but validation of thermal model is essential to conclude the design and further improvement in cavity cooling for higher beam power operation. For thermal validation, a measurement set up of water flow, temperatures are installed in the cavity. A suitable samples of data are collected during operation and analyzed. Statistical average temperature is taken to conclude heat load in the cavity and outer body temperatures. From this measured heat load and water cooling provided, ANSYS thermal model temperature distribution is generated. This temperature data at cavity surface is correlated to the measured temperature of cavity outer body, and therefore validated thermal model.

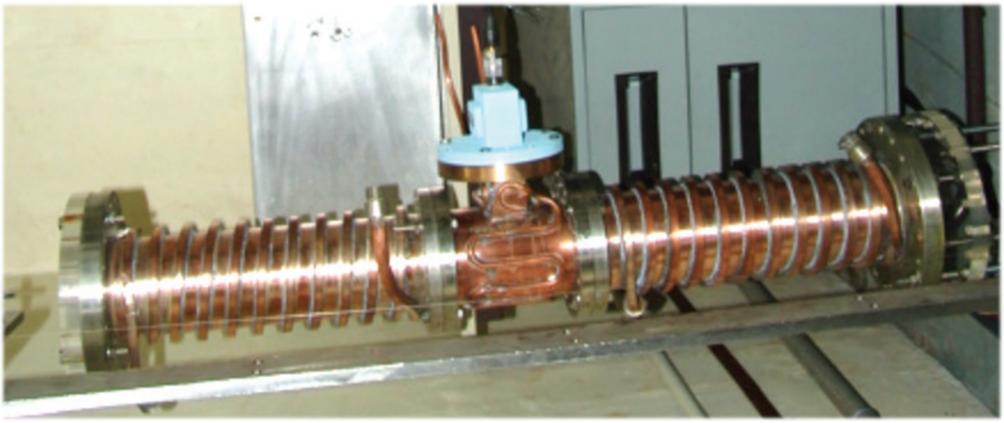

Figure 30.1: Structure to be thermally simulated.

30.2 Measurements Setup and Data Collection

To measure the heat load in the cavity it is essential to measure the water flow rate and temperature at inlet and outlet of each section of cavity. Therefore 3 nos of water flow meter are installed in each section and 4 nos of temperature sensors are installed on common inlet pipe and outlet pipe of each section. Apart from that 4 nos of temperature sensors are also installed in cavity top, middle and bottom flange locations where temperatures are expected to be higher from remaining cavity portion.

Beam Power Temperature measurement in ℃ Flow measurement in lpm

Table 30.1: Measurements table of water temperature and flow in cavity.

Beam Power	Temperature measurement in ℃				Flow measurement in lpm		
	Water in cavity (T1)	Water out Cavity bottom (T2)	Water out Cavity middle (T3)	Water out Cavity top (T4)	Cavity bottom	Cavity middle	Cavity top
0 kW	24.92	31.41	31.39	26.14	8	10	8
3 kW	31.17	27.84	26.51	31.57			
	31.78	31.45	27.24	29.06			
	31.65	31.09	26.75	31.69			
	23.95	31.29	31.53	31.78			
	24.9	27.3	26.2	27.9			
	31.1	26	26.3	26.5			
	31.65	31.09	26.9	31.4			
	23.34	26.14	31.2	26.8			
	24.8	27.36	26.26	31.09			
	31.5	31	26.8	31.7			
	22.8	31.4	24.8	26			
	31.53	27.96	26.87	31.21			
0 kW	22.25	23.34	23.95	23.95			
3 kW	23.09	26.25	24.79	26.75			
	23.59	26.75	31.29	27.24			
	26.51	29.3	27.48	29.67			
	31.05	27.72	26.63	31.45			
	23.71	26.51	31.53	27.24			
	23.61	31.99	31.53	27.6			

30.3 Thermal Heat Load Measurements in Cavity

All the measurements taken are at 3 kW beam power. The reference value of temperatures are also recorded when there is no beam. It is found that all temperature sensors are not showing the equal reading when water is flowing at no beam power. This initial variation in sensors reading is offset when calculating the temperature rise in each section. Beam Power Water Temperature rise in cavity

30.4 Summary of Power Balance in Linac System

Therefore total average thermal power loss in the cavity is 2.9 kW at 3 kW of beam power. In this measurement of temperatures, the variation in temperature rise are observed in each section of cavity. It is because of temperature response time of sensors and transient effects with the change in temperatures.

Table 30.2: Measurements table of water temperature and flow in cavity.

Beam Power	Water Temperature rise in cavity		
	Cavity Bottom	Cavity middle	Cavity top
3 kW	2.17	0.83	2.17
	2.23	0.96	2.06
	1.94	0.6	1.84
	0.85	1.1	0.65
	1.9	0.8	1.8
	0.4	0.7	0.3
	1.94	0.75	1.74
	2.3	1.3	2.25
	2.06	0.96	2.1
	2	0.8	2
	2.1	1.3	2
	1.93	0.84	1.63
	2.06	0.6	1.96
	2.06	0.6	1.96
	1.7		1.6
	2.17	0.6	2.2
	2.3	0.8	2.33
	1.9	0.8	2.7

Table 30.3: Heat load at various locations in the cavity.

Beam Power	Water average temperature rise (Δ T_m)	Water flow rate, m (Kg/sec)	Water flow rate, m (Kg/sec) Heat load (Watts) = $mC\Delta T_m$
Cavity Bottom, Q_b	2.1	0.133	1162
Cavity middle, Q_m	0.8	0.166	554.66
Cavity top, Q_t	2.15	0.133	1190
Total heat load in cavity (Q_b + Q_m + Q_t)			2907

Table 30.4: Summary of power balance in linac system.

RF power input to cavity	**Peak power: 3.2 MW, PRF: 300, Pulse width: 10 μs**
Average RF power input to cavity	9.6 kW (3.2×300×10)
Beam power of cavity	3 kW
Power loss in cavity	2.9 kW
Total forward power to cavity	5.9 kW
Total RF reflected power	3.7 kW

30.5 Thermal ANSYS Model of Linac Cavity

After the measurements of water flow and heat load in the cavity, a 2D axis symmetric thermal model is made in ANSYS. The total heat load measured is given as thermal heat flux on cavity inner surface as boundary conditions.

Table 30.5: Spatial distribution of the power density obtained from Ansys.

Z (cm)	**R (cm)**	**P (W/cm^2)**
0	4.133	–
0.2	4.133	4.986
0.89936	3.9996	4.963
1.3394	3.7535	5.026
2.1	2.233	5.414
2.1	1.6858	5.635
2.1	1.369	5.471
1.9805	1.0635	6.1
1.9081	1.0004	6.627
1.6873	0.84575	5.936
1.5594	0.6	2.99
1.6594	0.5	0.502
2.6	0.5	0.011

30.6 Calculation of Heat Transfer Coefficient Based on Measured Water Flow on Cooling Tube Surface

The water flow to the bottom and top part of the cavity is 8 lpm. The cooling tube for the cavity is of ID 6.25 mm and outside is square cross-Section of 10×10 mm^2. The convective heat transfer for the cooling channel is calculated manually as below: In Linac cavity water flows in tubes at inlet temperature of 25 ℃
Properties of Water at 25 ℃ ;
C_p = 4.18 kJ/kg.K; μ = 1000x10^{-6} N-s/ m^2; K = 0.60 W/m/K;
$P_r = \mu C_p/K = 6.97$;
Water Flow rate in tube = 8 lpm = 13.33 x 10^{-5} m^3/s;
Inside Cross-section area of each tube = $(\pi/4) \times D^2 = 30.6$ mm^2;
Velocity of water in tube (v) = 13.33 x 10^{-5} / (30.6×10^{-6}) = 4.35 m/s.
Reynold number, $R_e = \rho\, vD/\mu$ = 1000x4.35x6.25x10^{-3}/1000x10^{-6} = 27187;
R_e is greater than 10000; flow is fully developed turbulent flow.
Average Nusselt number in pipe flow calculation for heat transfer coefficient (h),
$Nu_D = 0.023\ R_e D^{(4/5)}\ P_r^n$ where n = 0.4 for heating Nu_D=177;
h_D /K = Nu_D Average convective heat transfer coefficient of water;
h = 177 × 0.60/6.25 × 10^{-3} = 16941 W/m^2 K.
If consider Fouling factor on water tube surface, f = 9 × 10^{-5} m^{2}K/W for DM water;
Effective heat transfer coefficient, $1/h_e = 1/h + f$
h_e=6711 W/m^2 K.
Therefore convective heat transfer coefficient of h = 6711 W/m^{2}K is applied to the inside surface of the cooling tube. The model is solved in ANSYS and following temperature distribution is obtained.

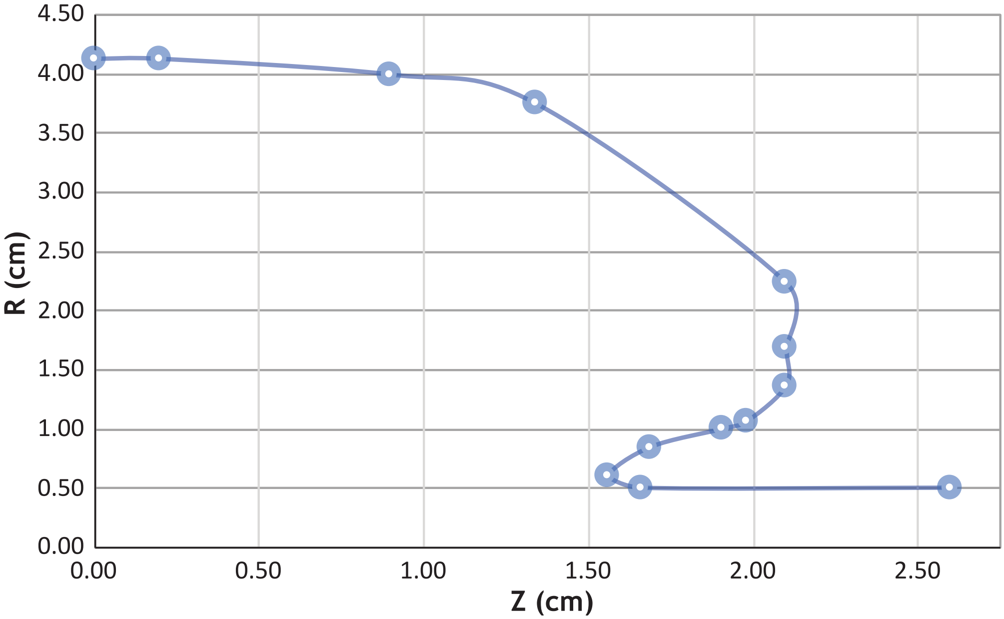

Figure 30.2: Thermal Flux distribution.

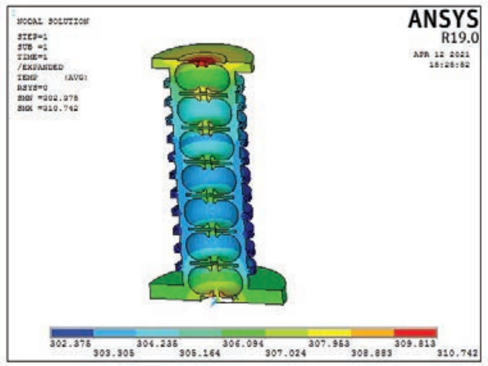

Figure 30.3: Temperature distribution inside cavity.

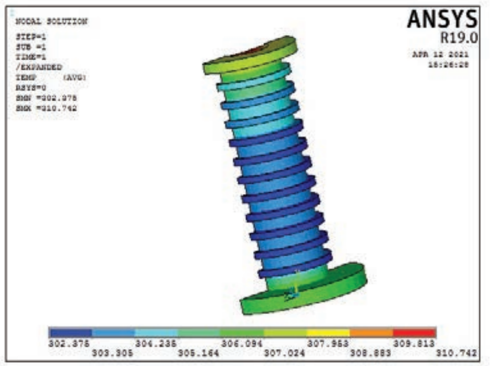

Figure 30.4: Temperature distribution outside cavity.

30.7 Comparison of Temperature in Cavity From Model and Measurements

From this analysis it is evident that hot spot temperature occurred at nose cone of cavity near the flange ends and it reaches to 310 K at 3 kW of beam power. Also the outer surface of cavity is 30-34 ℃ which has just 5-6 ℃ above the water temperatures. Our measurements of the cavity surface temperatures also shows the similar rise in temperature from the water inlet temperatures of cavity. Also temperature measure near the flange end shows little higher temperature which reflect the hot spot temperature occur at the nose cone of cavity near the flange ends. Therefore this reflection in temperature variation in cavity validates our thermal model in ANSYS.

Table 30.6: Thermal model in ANSYS and Measurements.

Cavity parts	**From Ansys model**	**From Measurements**
Cavity outer body face	30-34 ℃	All measurements are within 30-32 ℃
Cavity outer face near flange	32-36 ℃	All measurements are in 31-33 ℃

Our measurements of temperature data shows that it is about 1-2 ℃ lower than the thermal model. It is because of the thermal inertia of cavity especially near the flange end is very high and it takes time to reach the steady state. Our measurements are taken when various experiments are conducting and it often required to break the beam for various reasons.

30.8 Conclusions

This chapter discusses the thermal simulation aspect of RF linac section which is very importantfor linac operation point of view.